Technology of Bare Tether Current Collection

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Abstract

The outstanding problem for useful applications of electrodynamic tethers is obtaining sufficient electron current from the ionospheric plasma. Bare tether collectors, in which the conducting tether itself, left uninsulated over kilometers of its length, acts as the collecting anode, promise to attain currents of 10 A or more from reasonably sized systems. Current collection by a bare tether is also relatively insensitive to drops in electron density, which are regularly encountered on each revolution of an orbit. This makes nighttime operation feasible.

We show how the bare tether's high efficiency of current collection and ability to adjust to density variations follow from the orbital motion limited collection law of thin cylinders. We consider both upwardly deployed (power generation mode) and downwardly deployed (reboost mode) tethers, and present results that indicate how bare tether systems would perform as their magnetic and plasma environment varies in low earth orbit.

INTRODUCTION

Electrodynamic tethers (EDT), have been demonstrated to work in space, most notably by the TSS-1/R missions [8] and the Plasma Motor/Generator (PMG) experiment [3]. In each case, a long conductive tether, covered by an insulating sheath, served as a conductive path for electrons at one end of the system to a higher electrical potential at the other end. Charge exchange with the ionosphere occurred at the ends of the system. The positively biased subsatellite served as the electron collector for TSS-1/R. At the Shuttle end, electrons were ejected by electron guns, and positive ions were collected by metallic surfaces. PMG used hollow cathodes for charge exchange at each end of the system, which operated in both the motionally biased (generator) mode and in a battery-imposed reversed bias (motor) mode. The generally accepted explanation for TSS-1R's 1 A tether current flow after the tether break is that rapidly expelled air, which had been held within the tether before the break, ionized sufficiently to serve as a plasma contactor to expel electrons into the ionosphere.

While these experiments demonstrate that the basic concept of electrodynamic tethers is sound, they do not in themselves provide much encouragement for applications such as power generation or reboost for the International Space Station (ISS), which would require high currents on the order of 10 A. PMG attained 0.3 A, but failed to demonstrate efficient electron collection by a hollow cathode in space, particularly under low density conditions. TSS-1R generally exceeded predictions of electron current collection based on the static Parker-Murphy [5] limit by a factor of two or more, but still showed the expected square root dependence on bias voltage [8]. Thus the 1 A current collected by TSS-1R at a bias of around 1.5 kV implies that a 10 A current would require 150 kV, corresponding to a tether length of 850 km!

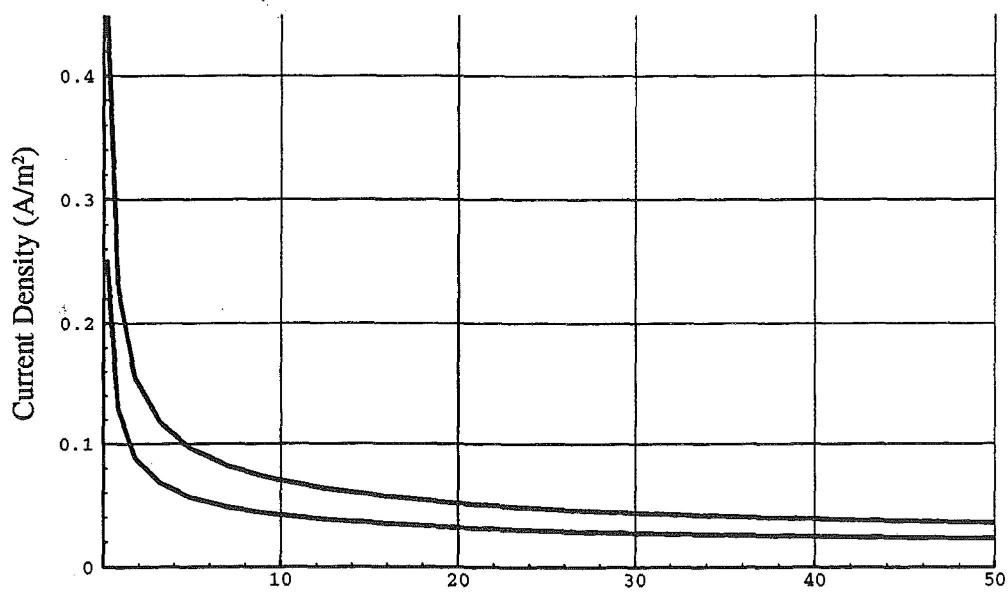

Figure 1. Current density versus collecting area for a passive sphere in typical daytime ionosphere. Upper curve for 1000 V bias, lower curve 300 V. $B_{earth} = 0.3$ G.

Of course, a larger sphere could be used to collect higher currents; but a natural law of diminishing returns quickly sets in, as Figure 1 shows. This is based on a current collection twice the Parker-Murphy limit, which implies lower and lower collection efficiency as the collecting area increases, due to the predominance of magnetic effects (binding of electrons to field lines). An electron density of $0.75 \times 10^{12}/m^3$ and an electron temperature of 0.15 eV have been assumed. TSS-1R should make us somewhat cautious in drawing firm conclusions based on magnetic limitations, but it does not provide a reason to ignore them.

Small probes (spherical or cylindrical) with dimensions less than the Debye length and gyroradius (both on the order of a centimeter in the ionosphere) are many times more efficient at collecting current (per surface area) than large balls such as the TSS collector. They avoid the effects of space charge shielding and magnetic guiding. A sphere of such dimensions is much too small to get multiamp currents with a reasonable bias voltage, however. Its area is determined by its radius, and cannot be made large without entering the region of rapidly diminishing returns.

A thin cylinder (wire), however, is still a thin cylinder, no matter how long it is. The current collection problem for a wire is basically two dimensional. Why not just use a long thin wire to collect current from the ionosphere? Collection should be very efficient, and the collecting area can be made large by the length (kilometers). That, in essence, is the bare tether idea developed by Sanmartín, Martínez-Sánchez, and Ahedo [6]. Here, in order to derive the general behavior of the bare tether system under variations of plasma density and motional electric field, we make the simplifying assumption of negligible tether resistance. The analysis shows that, due to the variable collecting area of a bare tether, current collection is much less sensitive to variations in plasma density than passive collection by a large sphere. We will demonstrate how this comes about for both the power generator and thruster modes of EDT operation. We also show that the efficiency of energy conversion is relatively steady under variations in motional electric field in both modes, but with different consequences for steadiness of the desired product in the two cases, since the motional E field is the energy source for the EDT generator. In all of the following analysis we assume an eastward moving tethered system in low earth orbit.

POWER GENERATOR MODE

By power generator mode, we mean an upwardly deployed tether, collecting electrons at the upper end of the system by virtue of the motional EMF, whether or not the tether current is being utilized. This is illustrated in Figure 2. At the upper end of the system, the tether itself, which has been left exposed to the ionosphere, serves as the electron collector. Electrons are expelled back into the ionosphere at the lower end by a plasma contactor, which maintains the deployment platform at a low bias with respect to the ambient plasma.

This is the configuration for the ProSEDS mission [2], which is scheduled for a flight in early 2000 as a Delta-II secondary payload to provide the first test in space of the bare tether concept. ProSEDS will in fact utilize electrical power from the tether to recharge its batteries and keep instruments, transmitters, and hollow cathode all working for the duration of the experiment, extending the useful lifetime of the system by days or weeks. Power generation is, however, only a secondary objective of the mission. The primary objectives relate to the magnetic force exerted on an EDT. In the power generator mode, the force is a drag force, which is a drawback if power generation is the goal. However, this drag can be a good thing, if accelerated re-entry is the goal. The force of the magnetic field on the current-carrying tether will also demonstrate the potential for a tether thruster in which the current flows in the opposite direction.

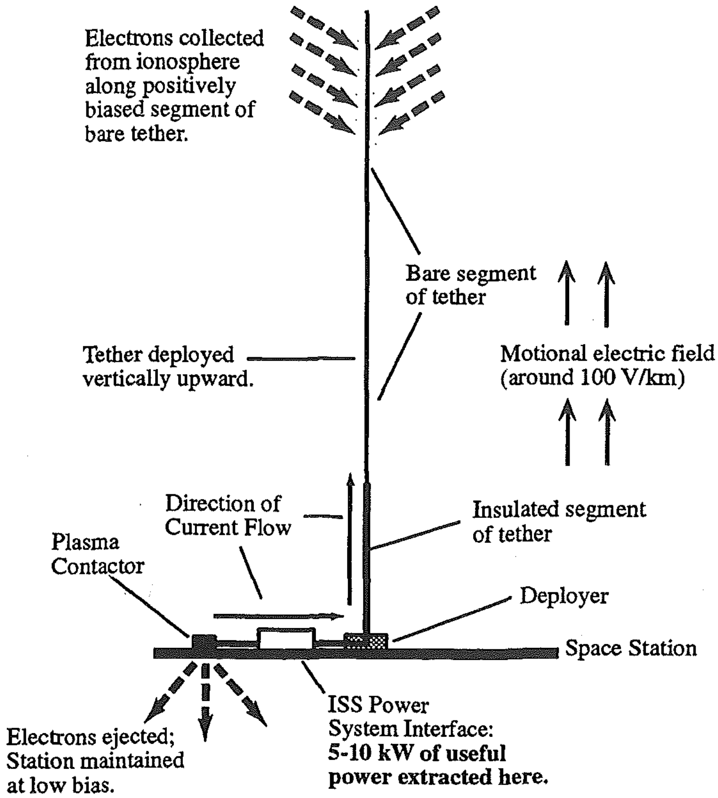

Figure 2. Schematic diagram of a possible EDT power generator for the ISS.

The basic operation of a bare tether power generator can be deduced from the voltage diagram in Figure 3. The vertical axis displays voltages, and the horizontal axis represents distance along the upwardly deployed tether. At the lower end of the tether (far right) a hollow cathode maintains the deployment platform (Station) at the local plasma potential.

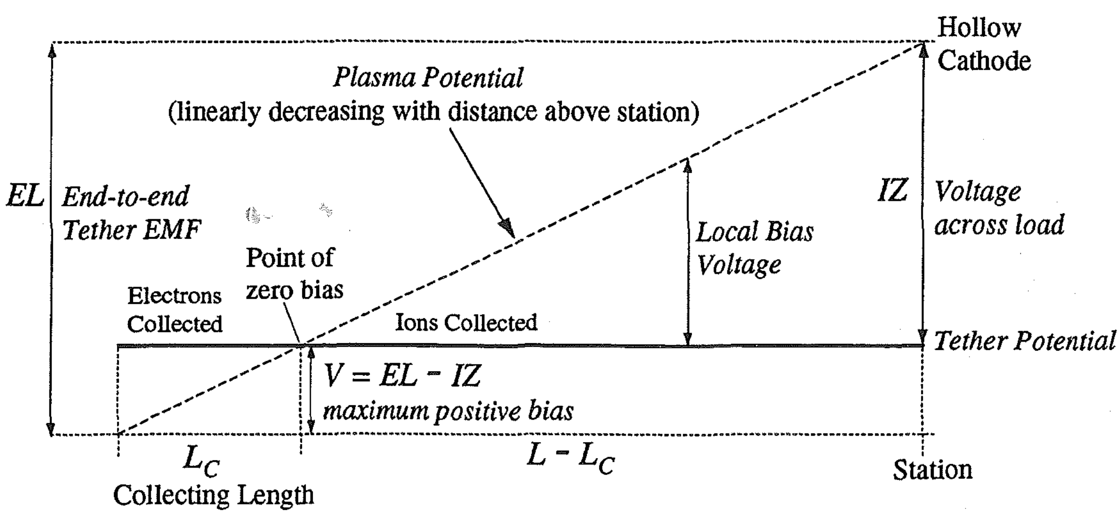

Figure 3. Voltage diagram for a bare tether power generator.

The plasma potential decreases linearly with distance up the tether (moving to left in the figure), reaching a maximum negative value of EL at the upper tip of the tether, where $E = \mathbf{v} \times \mathbf{B} \cdot \ell$ is the component of the motional electric field parallel to the tether, with $\mathbf{v}$ the orbital velocity, $\mathbf{B}$ the local geomagnetic field, ℓ a unit vector pointing up the tether, and L the tether length.

We ignore the ohmic voltage drop in the tether, since it is not the essential feature, and would be a secondary effect for an efficiently designed system. The tether is at a potential $-IZ$ with respect to the Station, with Z the load impedance and I the current delivered by the tether to the Station. Thus the tether is negatively biased with respect to the local plasma as we move up the tether until we reach a point of zero bias. From there on out to the upper tip, the tether is positively biased. It is along this segment, designated L_C in Figure 3, that the electron collection occurs. A much smaller ion current, which slightly reduces the current to the useful load, is collected along the negatively biased portion. We neglect this.

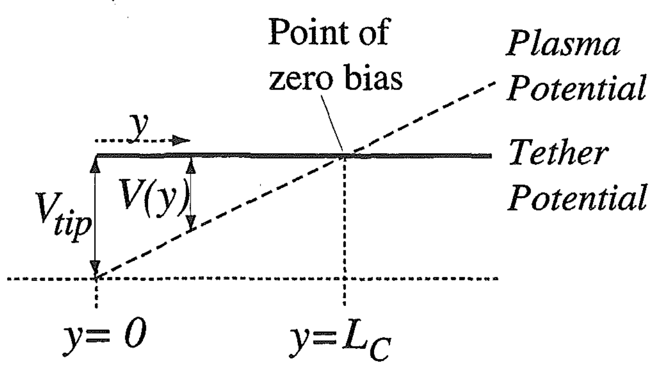

Figure 4. Voltage diagram in region of positive tether bias.

We now concentrate on the positively biased segment, in order to calculate the current collected by the wire. This is shown in Figure 4, where the local bias of the tether with respect to the plasma is indicated by $V(y)$. The maximum bias, which occurs at the tip, is given by $V_{tip} = EL - IZ$. We assume the cross-sectional dimensions of the tether are sufficiently small that electrons are collected in the orbital-motion-limited (OML) regime [4], where both space charge and magnetic effects are unimportant. Generally speaking this means, for a tether of circular cross section, a radius smaller than both the Debye length and the electron gyroradius. In the daytime ionosphere encountered in low earth orbit, these characteristic lengths are of the order of a centimeter. In a companion paper, Sanmartín and Estes [7] examine the limits of OML collection in more detail.

The fundamental equation for current collection by a wire along which the bias varies may be written as

$$\frac{dI(y)}{dy} = C'n\sqrt{V(y)}, \tag{1}$$

where n is the unperturbed electron density and the constant C' depends on the dimensions of the tether and the electron mass and charge [6]. Integrating (1) to get the total electron current collected, we obtain

$$I = \int_0^{L_C} \frac{dI}{dy} dy = \tfrac{2}{3} \frac{C'}{E} n V_{tip}^{\frac{3}{2}} = \tfrac{2}{3} C' n \sqrt{E} L_C^{\frac{3}{2}}. \qquad (2)$$

Thus the current collected is proportional to the 3/2 power of the tip bias, or equivalently, the 3/2 power of the collecting length. This 3/2 power dependence has important consequences and gives the bare tether a significant edge over passive spherical collectors, in terms of dependence on plasma density, as we shall see. The primary advantage comes from the size of the factor C', however. This can be seen dramatically by comparing a bare tether collector to two spherical collectors, which we can term equivalent to it by different criteria. We ignore the tether resistance in considering these ideal systems.

For the bare tether system, we take a 10 km-long wire with circular cross section and radius of 3.6 mm (well within the OML collecting regime). It generates 15 kw of power for the reference point plasma density of 7.5 $10^{11}/m^3$ and motional electric field of 0.18 V/m. This is 10 A into a 150 ohm impedance. The wire collects electrons over 1.7 km for the reference point conditions; this corresponds to a collecting area of 39 m^2. The magnetic drag is around 2.25 N.

Taking passive sphere electron collection to be twice the Parker-Murphy limit, we can define an equivalent ball system 1, such that it also generates 15 kw of power with a 10 km tether at the reference point conditions (assuming in addition an electron thermal energy of 0.15 ev and a magnetic field of 0.3 G). Such a ball turns out to be enormous. Its radius is 8.3 m, so that it is roughly the size of a five-storey building. Its area is 872 m^2 (over 20 times greater than the wire's collecting area at the reference point). The mass, drag, and the operational difficulties that deploying and maintaining such a large system would entail make it an implausible equivalent in reality.

Another approach would be to take an equal-area sphere. The wire will collect electrons along 6.1 km of its length when the plasma density decreases by a factor of ten. Equivalent ball system 2 will be defined to have the same collecting area as 6.1 km length of tether. The ball radius is then 3.4 meters. The tether has to be 89 km long to achieve 15 kw under the reference point conditions, and the corresponding magnetic drag is around 20 N!

When we look at what happens as the system passes into darkness, where plasma densities drop by a factor of ten or more, we find the bare tether further demonstrates its superiority to the "standard" passive ball collector.

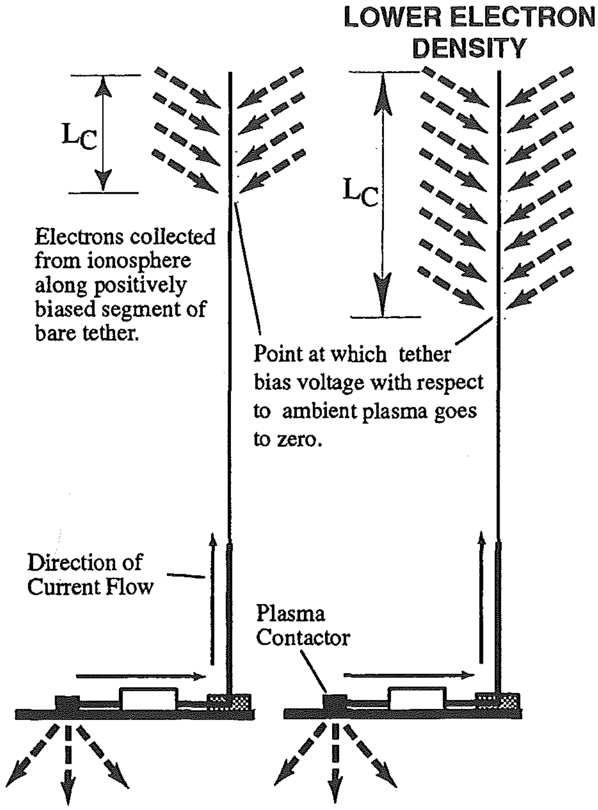

Figure 5. The bare tether power generator automatically adjusts to a density decrease.

At first glance equation (2) might appear to be saying that the current is linear in the electron density n. However, this impression is seen to be false when we write

$$I = C\frac{n}{E}(EL - IZ)^{\frac{3}{2}}. \tag{3}$$

The current will clearly have to decrease if the electron density decreases. But a decrease in current I implies both an increase in the tip voltage and the collecting length. The zero bias point moves down the tether. This is illustrated in Figure 5.

This corresponds to an increase in the factor in (3) with the 3/2 power. If IZ is comparable to EL (high efficiency case), this factor can largely offset the decrease in density. We consider the case where the efficiency

$$\varepsilon \approx \frac{IZ}{EL}$$

is near unity.

From (3) we obtain the derivative of the current with respect to the density n as

$$\frac{dI}{dn}\left(1+\tfrac{3}{2}\frac{IZ}{EL-IZ}\right)=\frac{I}{n}. \tag{4}$$

Applying the high efficiency condition, we obtain

$$\frac{d(EL-IZ)}{dn}\approx-\tfrac{2}{3}\frac{(EL-IZ)}{n}. \tag{5}$$

This yields an approximate solution good so long as n doesn't take us out of the regime of high efficiency:

$$I=\frac{EL}{Z}\left(1-\left(\frac{n_0}{n}\right)^{\frac{2}{3}}\frac{L_C^0}{L}\right), \tag{6}$$

where n_0 and L^0_C are the initial plasma density and collecting length, respectively. Due to the 2/3 power variation in the density ratio, the condition of high efficiency can still be maintained for a relatively large drop in plasma density.

When we carry through the same analysis for a spherical collector, assuming a $V^{1/2}$ law for collection, we arrive at

$$I=\frac{EL}{Z}\left(1-\left(\frac{n_0}{n}\right)^{2}(1-\varepsilon)\right), \tag{7}$$

where ε is the initial efficiency of energy conversion. This shows that the variation with n is much stronger in the case of the sphere. Expression (7) will clearly run out of the high efficiency regime with relatively small decreases in n.

Figures 6 and 7 compare the performance of the 10-km bare tether system and the equivalent ball system 1 previously considered under plasma density variations of the sort that can be encountered in a single revolution in low earth orbit. The motional EMF is held constant. The power generated , which is proportional to the square of the current, is shown in Figure 6, and the efficiency of energy conversion, which is nearly proportional to the current, is shown in Figure 7.

The motional electric field component $E=\mathbf{v}\times\mathbf{B}\cdot\hat{\ell}$, which provides the voltage that collects the current, also varies around an orbit. We now consider how variations in E affect the current collection. As before, we assume we are in the high efficiency regime to

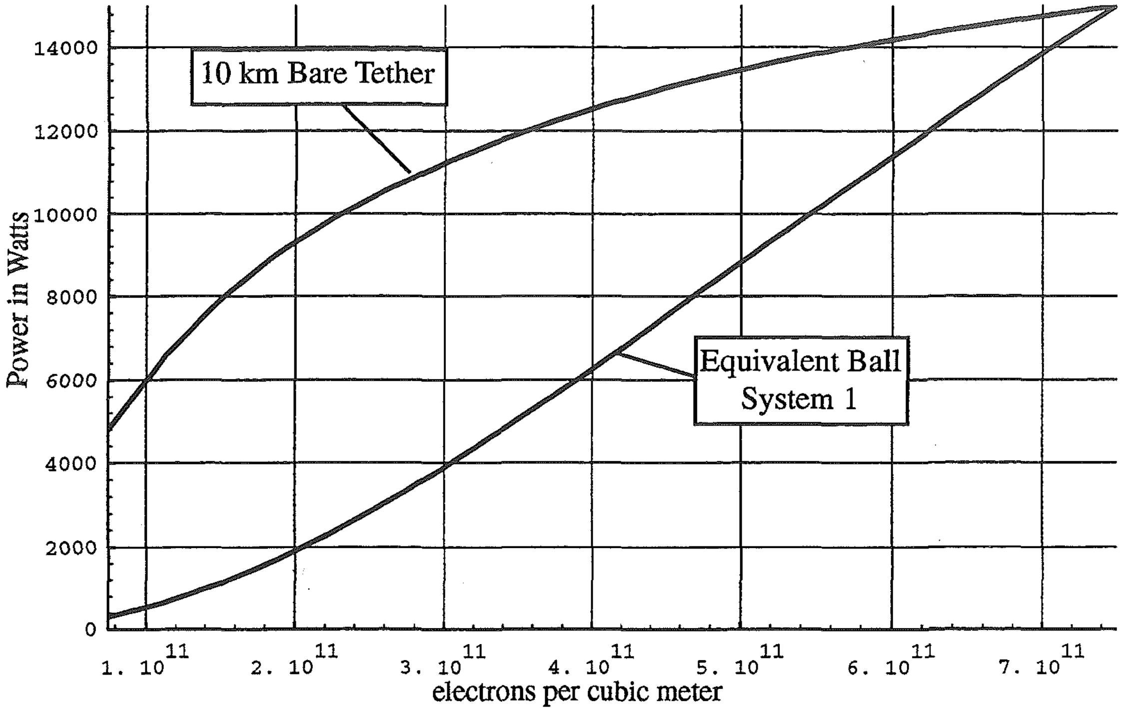

Figure 6. Power variations with electron density for ideal 10-km bare wire and equivalent ball system 1 (equal tether length). Both generate 15 kw at the reference point.

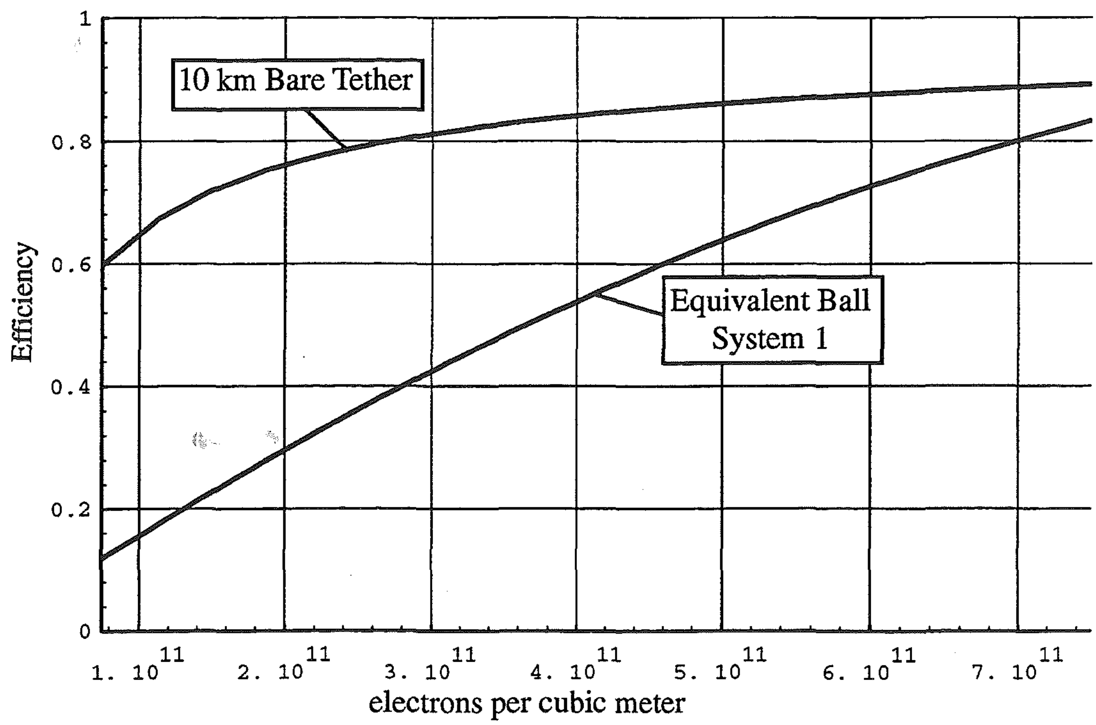

Figure 7. Efficiency of orbital to electrical energy conversion for ideal 10-km bare tether and equivalent ball system 1 (equal tether length) over a range of plasma densities.

start, i.e., plasma density is sufficient. Then the derivative of the current with respect to E can be found from

$$\frac{dI}{dE}\left(1+\tfrac{3}{2}\frac{IZ}{EL-IZ}\right)=I\frac{(EL-IZ)+\tfrac{3}{2}EL}{E(EL-IZ)}\ , \tag{8}$$

which simplifies to

$$\frac{dI}{dE}\approx\frac{L}{Z}$$

so long as the efficiency is near unity. Then we have $\frac{I}{E}\approx\frac{I_o}{E_o}$, so long as $E>>(1-\varepsilon_o)E_0$,

where E_o and ε_o are the original electric field and efficiency, respectively.

The good news out of this result is that, if we are converting orbital energy to electrical at high efficiency, we can maintain good efficiency even with large decreases in the motional electric field (say by a factor of 3 for $\varepsilon_o = .9$).

However, the power will decrease roughly with the square of the motional electric field. There is no 'cure' for this problem, since the electric field is our energy source. The bare tether is no different from a passive sphere tethered system in this respect. We can boost the power, at the expense of efficiency, by decreasing the load impedance. Thus a variable impedance system is required to maximize orbital average power and to minimize power variations. The tradeoff is average power versus efficiency, so system design must take into account which is more important, keeping in mind that lower efficiency means higher magnetic drag, which must be compensated for to avoid orbital decay.

Figure 8 shows an example of how the combined effects of plasma density and motional EMF variations would affect a real bare tether generator. These calculations have been made using the full equations of reference [6], with tether resistance included. The tether considered is made of aluminum and is 18 km long. The tether geometry is that of a tape 0.7 mm by 11 mm. The impedance is varied to keep the maximum instantaneous power below 12 kw, though higher powers (at lower efficiency) could be reached, assuming plasma contactors could handle the higher currents that would be collected. The impedance is lowered to achieve maximum power when troughs in motional E field are encountered.

In line with our approximate calculations, the electric field is seen largely to determine performance. This is a near worse case example, with troughs in motional E field and density overlapping, but density variations are clearly a secondary effect.

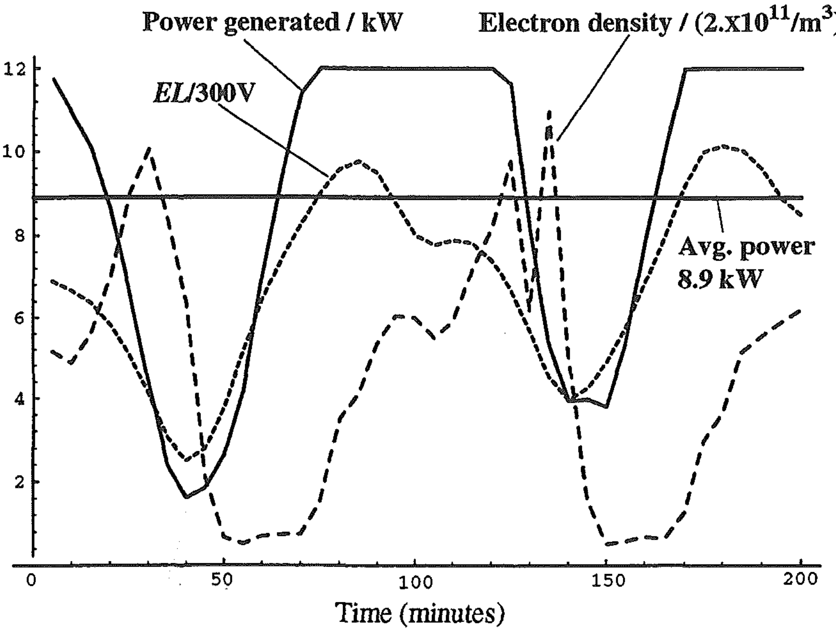

Figure 8. Power generated by a 'realistic' bare tether generator as it encounters varying motional E field and electron density around an ISS-type orbit.

THRUSTER MODE

The potential application of EDT that has drawn the most interest recently is their use for propellantless reboost of the International Space Station [1] or for orbit modification. In either case, the (partially) bare tether is deployed downward and biased positively with respect to the plasma by means of a power supply. Thus a tether based system is a type of electrical propulsion system. Electrons are collected along a portion of the exposed metallic wire. In contrast to the case of the power generator, the maximum bias voltage occurs at the end of the insulation and decreases as we move downward toward the tip of the tether. Despite this difference, the analysis of the system yields results that are analogous to those we have already obtained for the power generator. The thrust comes from the action of the magnetic field on the current in the wire. The general setup is illustrated in Figure 9.

The voltage diagram in Figure 10 contains the basic physics of the bare tether thruster operation. The vertical axis displays voltages, and the horizontal axis represents distance along the downwardly deployed tether. At the upper end of the tether (far left) a hollow cathode maintains the deployment platform (Station) at the local plasma potential. The plasma potential increases linearly with distance down the tether (moving to the right in Figure 10), reaching a maximum positive value of EL at the lower tip of the tether, where L is the tether length and E is the component of motional electric field along the tether, as defined for the corresponding discussion of Figure 3 in the preceding section.

A comparison of the voltage diagram in Figure 10 with the corresponding Figure 3 for the power generator reveals how the two modes of operation differ. The main difference

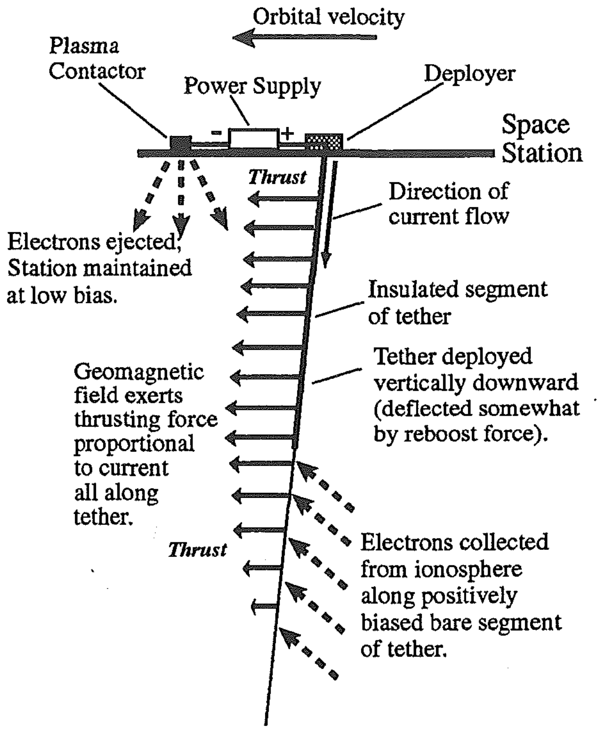

Figure 9. Schematic diagram of a possible bare tether thruster for the ISS.

is that the motionally induced voltage must be overcome by a supplied voltage at the platform in order to drive a current in a direction opposite to the "natural" one.

As before, we ignore the ohmic voltage drop in the tether. We assume a constant input power P to drive the tether current. The tether is at a positive potential P/I with respect

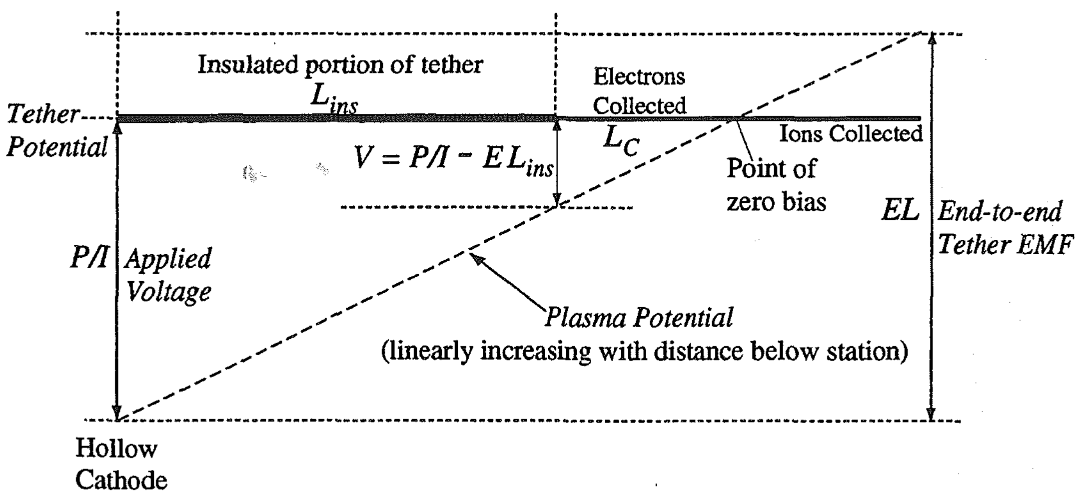

Figure 10. Voltage diagram for a bare tether thruster.

to the Station, with I the current delivered by the tether to the Station. Thus the tether is positively biased with respect to the local plasma as we move down the tether until we reach a point of zero bias. For reasons that will be discussed later, the tether needs to be insulated for a certain length L_{ins} of the upper (attached) portion. In order to collect a current, the supplied voltage must be greater than EL_{ins}. It is along the bare segment of positive tether bias, designated L_C in Figure 10, that electrons are collected. From there on out to the lower tip, the tether is negatively biased. An obvious difference from the case of the power generator is that here the maximum bias voltage occurs at the electron-collecting point on the tether closest to the attachment point.

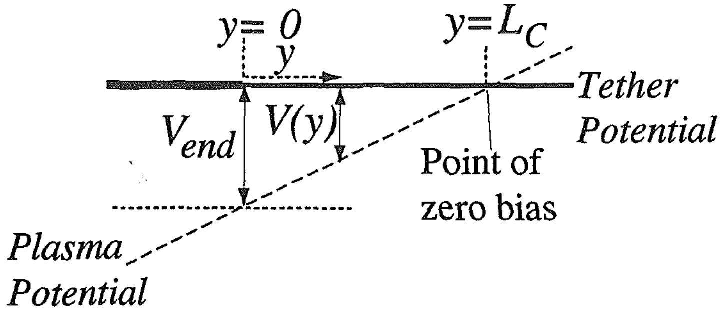

Figure 11. Voltage diagram in region of positive tether bias.

In order to obtain the total electron current collected by the tether we apply the basic equation (1) of OML collection to the situation illustrated in Figure 11. Despite the different source of the bias voltage in the two generator and thruster cases, the integrals for thecurrent in the two cases are completely analogous with the V_{tip} of the generator replaced by the bias voltage at the end of the insulation $V_{end} = P/I - EL_{ins}$. This is clear when Figure 11 is compared with Figure 4.

Integrating over the collecting length, as in the case of the generator, we obtain for the current in the insulated part of the tether

$$I = C\frac{n}{E}V_{end}^{\frac{3}{2}}. \tag{9}$$

For zero tether resistance, the efficiency of energy conversion may be written as

$$\varepsilon = \tfrac{3}{5} + \tfrac{2}{5}\frac{I}{P}EL_{ins}, \tag{10}$$

so that the high efficiency condition is

$$EL_{ins} \approx \frac{P}{I}.$$

The magnetic thrust force on the tether is proportional to the integral of the current along the tether. Lengthening the insulated section forces current to flow over a longer portion of the tether. Although the current reaching the upper platform (for constant input power) decreases as the insulated length increases, the integral of the current along the tether (and thus the force) increases. Thus the efficiency of electrical to mechanical energy conversion increases with the insulated tether length. This is illustrated in Figure 12. The design of a tether thruster has to balance the need to keep tether mass low, the increased efficiency that comes with greater insulated length, and the necessity for having sufficient bare tether available to collect current under conditions of reduced plasma density.

As in the case of the generator, provided the system has been designed with a bare portion that is suffiently long, the bare tether reboost system can offset to a degree the effect of lower plasma densities, by automatically extending the portion of the bare wire on which electrons are collected.

The bias voltage at the end of the insulated portion of the tether (and the collecting length) increase as the current drops. Again the factor raised to the 3/2 power in the current eqation increases:

$$I = C\frac{n}{E}\left(P/I - EL_{ins}\right)^{\frac{3}{2}}. \tag{11}$$

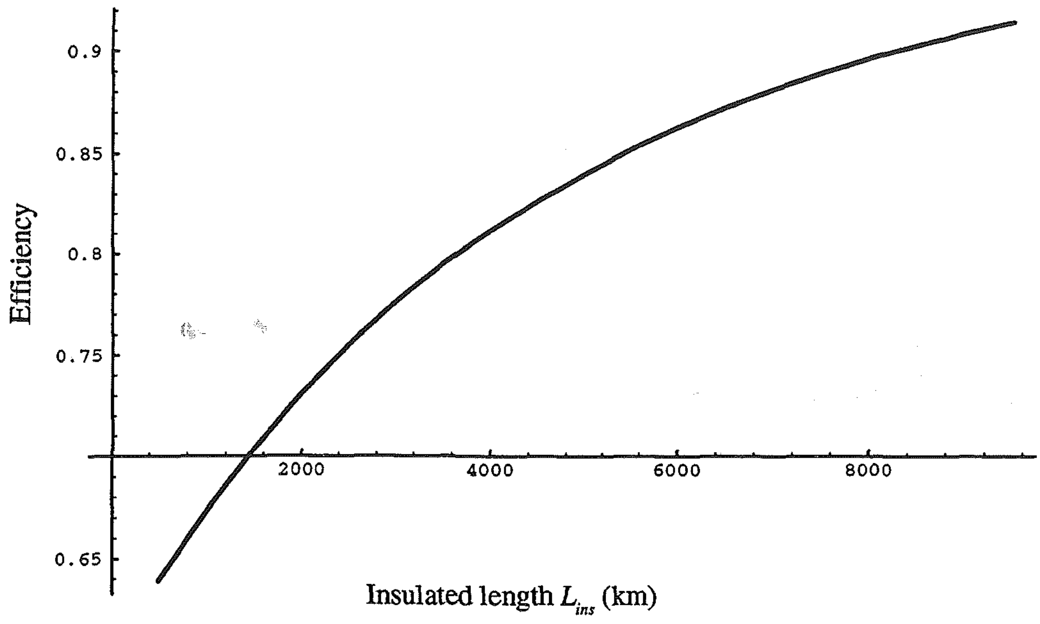

Figure 12. Electrical to orbital energy conversion as a function of insulated tether length.

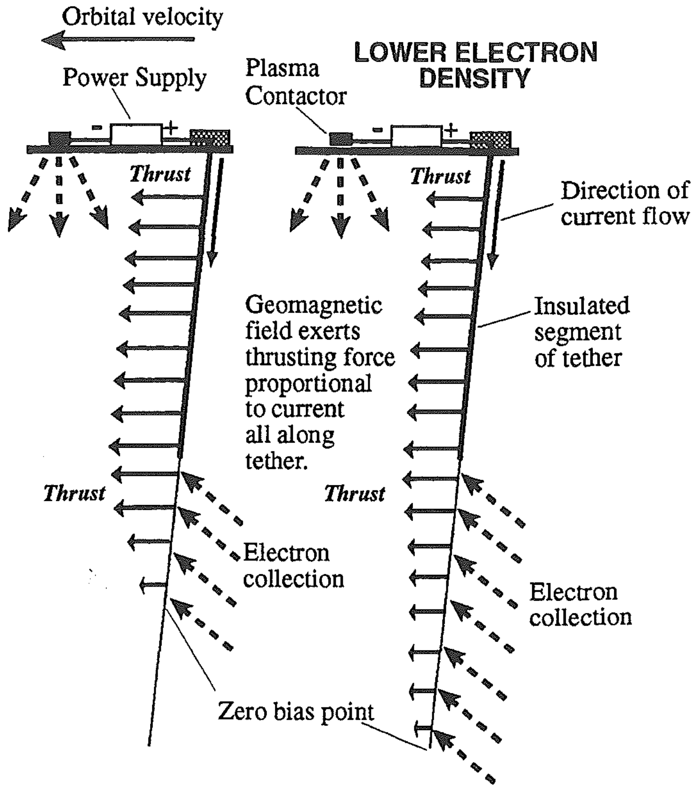

Figure 13. The bare tether thruster automatically adjusts to a drop in plasma density.

It is more convenient to work with the input voltage $V = P/I$, which satisfies

$$V = \frac{PE}{Cn}\left(V - EL_{ins}\right)^{-\frac{3}{2}} . \tag{12}$$

Proceeding as before, in the high efficiency regime, we get

$$\frac{d\left(V - EL_{ins}\right)}{dn} \approx -\frac{2}{3}\frac{\left(V - EL_{ins}\right)}{n} . \tag{13}$$

This has the approximate solution

$$V = EL_{ins} + V_{end}^{0}\left(\frac{n_0}{n}\right)^{\frac{2}{3}} \tag{14}$$

in the high efficiency region, which can be written as

$$I \approx \frac{P}{EL_{ins}}\left(1-\left(\frac{n_0}{n}\right)^{\frac{2}{3}}\frac{L_C^0}{L_{ins}}\right), \tag{15}$$

which, not surprisingly, is very similar to the result found for the generator, since the energy source is constant in each case and the current collection equations are the same.

If we carry out the same analysis for a ball collector at the end of an insulated tether of length L, we obtain

$$I \approx \frac{P}{EL}\left(1-\frac{V_0}{EL}\left(\frac{n_0}{n}\right)^2\right), \tag{16}$$

where V_0 is the original bias voltage of the sphere. This will quickly violate the condition of the approximation as n decreases.

Now we consider variations in the electric field component E. The situation is different from that of the generator mode, where E drives the current. Here, E works against the current, and a lower E means a higher current for constant input power, as there is a lower voltage to overcome.

The derivative of the input voltage V with respect to the motional field component along the tether E is, in the high efficiency region, given by

$$\frac{dV}{dE} \approx L_{ins}. \tag{17}$$

This implies $I_0E_0 \approx IE$, so long as the efficiency $\varepsilon \approx 1-\frac{3}{5}\frac{V_{end}^0}{EL_{ins}}$ is not far from unity. The efficiency (and thrust) decrease with decreasing E, but slowly. We also found a steady efficiency under E variations in the power generator case, but the consequences were quite different there, as E was the energy source.

A bare tether thruster, designed for high efficiency, has been shown to generate a steady thrust under variations in motional E field and plasma density, so long as the deviations are not too large. What about a "real world" system? Figures 14(a)-(f) illustrate the operation of a system that might provide reboost for the ISS, utilizing only 5 kw of the Station's solar power. Except for the length, the tether is similar to the one whose perfomance was displayed in Figure 8 in the power generator case. The system does not truly operate at high efficiency (average efficiency is around 0.66) as assumed in our calculations, since the desire to minimize perturbations to the station led to the choice of a tether only 7 km long. The insulated portion of the tether is 5 km long. Nonetheless, the thrust is seen to vary only by a factor of 2.5, while the density varies by a factor of 15 and the E field by a factor of four.

By comparing Figures 14(b) and 14(c), one sees that when operating at its highest efficiency (around 0.8), the system rides smoothly over fluctuations in motional electric field. The adustment of the system to nighttime density conditions can be seen in Figures 14(a), 14(d), and 14(f). The bias voltage at the end of the insulation shown if Figure 14(d) peaks during the nighttime density troughs of Figure 14(a), while the collecting length extends to the very tip of the tether in Figure 14(f).

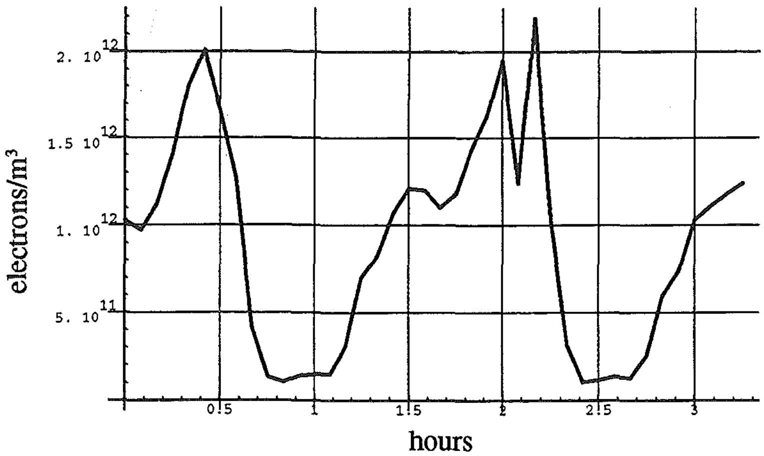

Figure 14(a). Plasma density encontered in two revolutions of ISS orbit.

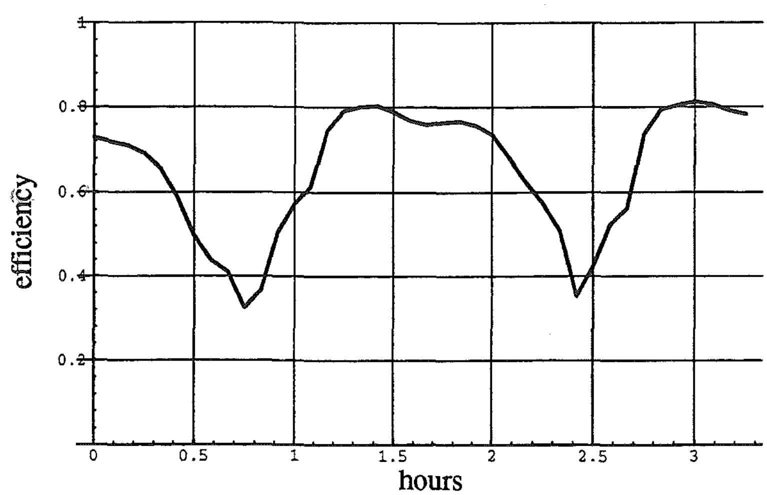

Figure 14(b). Efficiency of electrical to mechanical energy conversion.

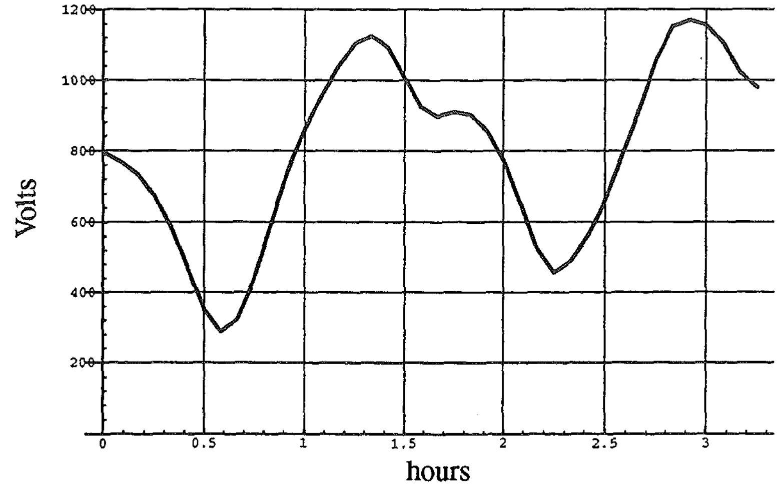

Figure 14(c). *EL* (motional EMF) around two revolutions of ISS orbit.

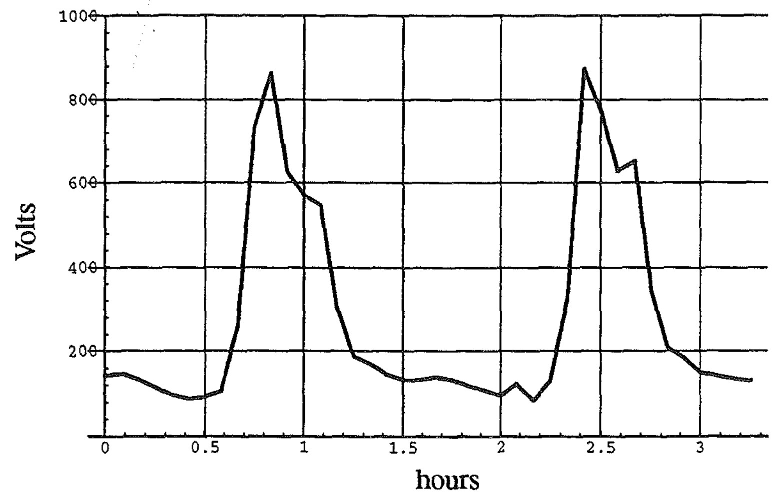

Figure 14(d). Bias voltage at end of insulation (V_{end}) in two revolutions of ISS orbit.

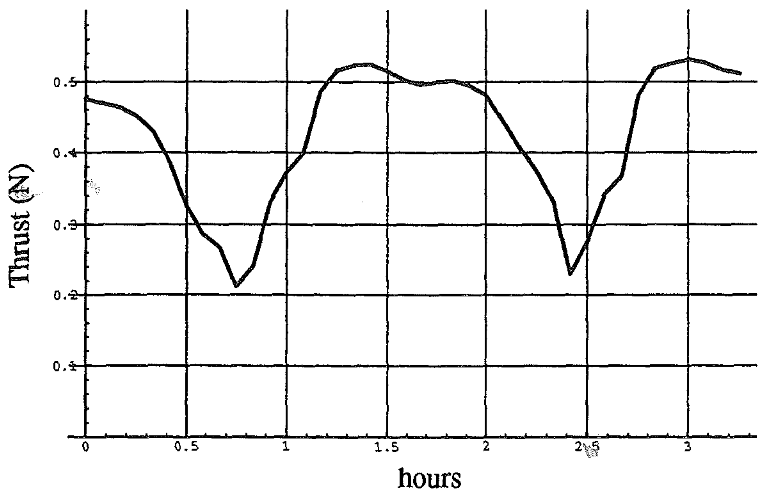

Figure 14(e). Thrust generated around two revolutions of ISS orbit. .

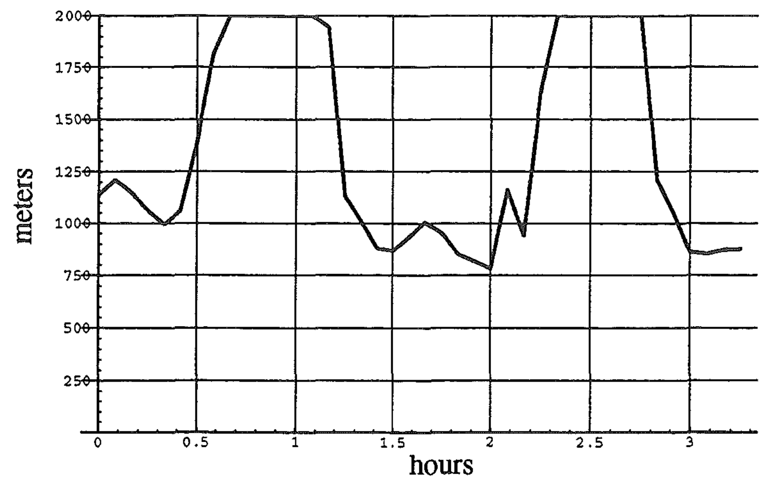

Figure 14(f). Collecting length L_c around two revolutions of ISS orbit.

As might be expected, the thrust generated is roughly proportional to the input power. The signifance of this is that a single bare tether system could generate more thrust depending upon need and available power. It would be quite flexible in that regard. This is shown for a 10 km system in Figure 15.

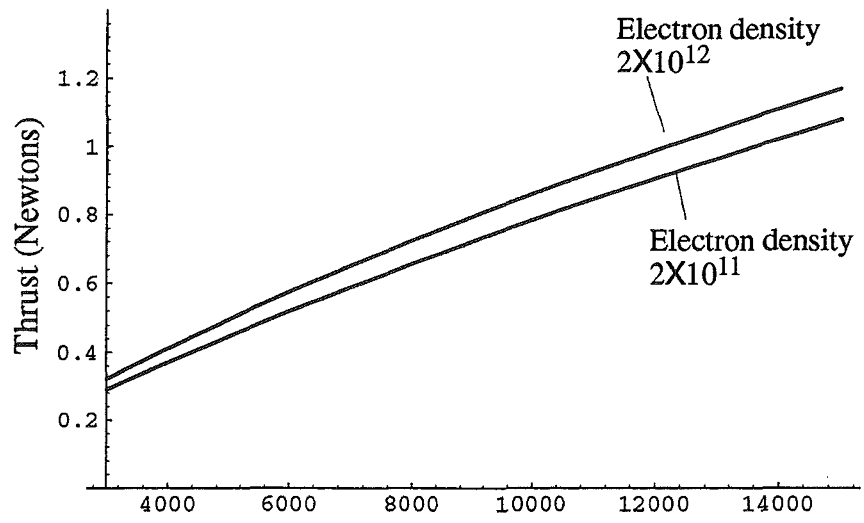

Figure 15. Thrust generated as a function of input power for two plasma densities.

CONCLUSIONS

Bare tethers promise to collect currents in the 10 A range with reasonably sized, simple systems. In addition to efficient current collection, both power generator and reboost systems based on bare tethers should be able to operate night and day, because of the selfadjusting collecting area inherent in the system. The strength of the magnetic field and its orientation with respect to the system's velocity vector (which determine the component of motional electric field along the tether) mainly determine power variations for any EDT power generator, though high efficiency operation can be maintained if variations in power are acceptable. A bare tether operating as a thruster at constant input power with high efficiency should maintain a fairly steady thrust even with wide variations in motional electric field and plasma density.

ACKNOWLEDGMENTS

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